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(NASA-CR-155617) PRELIMINARY DESIGN AND
FABRICATION ASSESSMENT Final Report (ILC
Industries, Inc., Frederica, Del.) 39 p
HC A03/MF A01 CSCL 22B

N78-17126

G3/15 Unclass
04194

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THIS SUPPLEMENTAL BOOKLET CONTAINS SECTION 5.0,
SAIL DESIGN CRITERIA (SQUARE SAIL) AND SECTION
6.0, HANDLING AND FABRICATION PLAN (SQUARE SAIL)
WHICH COMPLETES THE REQUIREMENTS FOR THE FINAL
REPORT NUMBER 0003-70065 PREVIOUSLY TRANSMITTED
ON JULY 4, 1977.

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5.0 SAIL DESIGN CRITERIA (SQUARE SAIL)

5.1 Material

The material to be used is 0.1 mil Kapton, a DuPont product. Refer to Section 3.1 for a description and information on current "state-of-the-art" of Kapton and its application to the Solar Sail Project. •

5.2 Shape

5.2.1 Contour

The square solar sail is basically a square sheet of 0.1 mil film, 850 meters on a side. The sheet is attached to the structure at five (5) points, one at each of the four corners and one at the center. The rigid boom structure to which the sail sheet is attached consists of four (4) diagonal booms and a central apex boom which suspends the center of the sheet. Apex height adjustment up to 10 meters is possible with the most recent configuration.

Diagonal support tendons are suspended from the apex to each diagonal boom to transfer the accumulated sail loading to the spacecraft structure. The sail film edge between corners is scallop shaped and reinforced with a cord or tape to accumulate sail loads and transmit them to the diagonal booms.

Each sail sheet corner is attached to an outhaul lanyard which is connected to a winch on the diagonal boom. The system is designed with a nominal adjustment of 6 meters inhaul/outhaul at each corner.

The optimized loaded shape of the square sail is determined by computer analysis and will be provided by specific film panel patterning. The final shape definition would be based on a trade-off between flight performance characteristics and film stress distribution.

5.2.2 Edge Scallops

The straight line length along the side of the sail between corners is 850 meters. Along this length the edge is scalloped inward and downward (toward shade side), the maximum scallop throat depth is 21.25 meters in the X-Y plane and 9.24 meters in the Z direction. A graphite prepreg tape similar to that used for the catenary edges of the spinning sail is proposed for these scalloped edges. The tape could be bonded to the square sail film with a polyimide adhesive in the same manner as in the spinning sail concept.

5.2.3 Center Hole

A 40 meter diameter center hole is provided in the center of the sail to provide clearance to the payload package. Also, the four sail corners are attached to the structure with cables or lanyards which are used to adjust the tension and "trim" the sail. In the X-Y plane, the 40 meter hole will be scalloped or catenaried to carry sail loads into the center spacecraft axis. The edge of this hole could be reinforced with a graphite prepreg tape similar to the edge scallop tape.

5.2.4 Reinforcements, Grommets, Fillets

Various types of film reinforcements will be required at localized high stress areas to prevent excessive film loading and potential sail sheet degradation. The sail corners, where three (3) reinforcement tapes converge, are expected to be areas of high film stress. It may be possible to dissipate these stresses into the film with load distribution tapes or to reinforce the sail sheet so that it can withstand a higher stress loading in these areas.

An alternate solution which has been considered, is to remove some film material from the high stress corners and allow all loads to be transferred to the diagonal and edge reinforcement tapes to be carried directly to the corners.

5.3 Joints, Seams

5.3.1 Basic

The investigations made in Section 3.2 for the spinning sail are applicable to the square sail with the exception of the 1% fullness requirement. The recommended basic seam configuration is a butt seam with overtape on sun side (See Section 3.2.2.3).

5.3.2 Ripstops

Potential tears in the sail film material are to be restricted to a maximum propagation of 8 meters before encountering a rip stopping device.

The current ripstop configuration involves the use of Kapton tapes bonded across the raw sheet material at 8 meter intervals. It is anticipated that these tapes will be 0.5 cm wide by 0.3 mil thick and will be applied to the sail sheet material at a sub-assembly production level.

The square solar sail material will be perforated with small mechanically punched holes to permit entrapped air to escape as film layers are accumulated, and also, to facilitate electrical coupling of the two film sides.

These holes will serve as tear resistant features; the force to initiate a tear after it has propagated into a hole is quite higher than the basic material tear propagation value. Results of tear tests run to quantify their difference are shown in Section 3.3.

5.3.3 Edges

The square sail edges are scalloped or catenaried to permit a more uniform stress distribution in the sail film. Each edge is approximately 852 meters long and will require a reinforcement similar to the baseline graphite reinforced polyimide tape used elsewhere. During manufacture, it would be necessary to seal across the sail edge as each width of new material is added. Thus, a requirement exists to be able to add short lengths of edge reinforcement tapes as the seams are crossed. These tapes must be secured to the film edge and also the adjacent pieces of tape.

5.3.4 Diagonals

The four (4) diagonals are each suspended from inhaul/outhaul lines. Due to the sail film loading, the diagonals assume a catenary shape. Each diagonal is 602 meters long and segments of diagonal reinforcement would be spliced in by overlap sealing.

The 0.1 mil Kapton sail film will be heat sealed to the diagonals and will cross the diagonals so that the edge of the 1 meter wide sail film sheets is perpendicular to the diagonal reinforcement.

6.0 HANDLING AND FABRICATION PLAN (SQUARE SAIL)

6.1 Seam Direction and Shaping

6.1.1 General

The solar sail shape description is very critical because of overall vehicle performance and film stress distribution. It is desired to simulate a double curved surface with flat patterned strips of film in such an arrangement as to provide an accurate shape and planform consistent with a manufacturing scheme which minimizes sail handling and film abuse.

The extreme size of the solar sail sheet makes fabrication in segments, quadrants, or other lower level subassemblies very impractical. Any conceivable method of utilizing a subassembly approach to manufacturing would necessitate the folding or rolling of individual assemblies to prepare them for attachment to subsequent sections.

This redundant material handling exposure would seriously affect the reliability of quality control data since several folding and joining procedures would be conducted after the on-line quality control data was obtained. No final inspection would be possible to detect physical property degradation resulting from such handling.

Three baseline patterning concepts were initially proposed for providing the required square sail shape contour. In each of these cases, it would be necessary to utilize variable width

film panels to achieve the double curved surface desired in each of the sail's quadrants. The three patterning concepts and their fabrication ramifications are described below.

6.1.2 Seams Parallel to One Side (Figure 6-1)

This basic seaming scheme would require sealing of adjacent panels of film each approximately 850 meters long. In this scheme it would be necessary to seal over the diagonal reinforcements as production progressed across the sail.

The major problem anticipated with this concept was the discrete seam direction change required at the diagonal intersections. Seams would approach and leave the diagonal at acute angles and would not be continuous across diagonals. Their direction changes would require tucks or pleats to be taken in the film panels at each diagonal. Such material folding or wrinkling is cause for great concern from a temperature control standpoint.

6.1.3 Seams Parallel to Sides (Figure 6-2)

The intent in this concept was to devise a method of folding the sail at the diagonals to permit "straight" sealing around the sail's perimeter. It was soon apparent that this, if possible, would cause additional problems since the fourth diagonal seam could never be folded and positioned for final closure.

6.1.4 Seams Parallel to One Diagonal (Figure 6-3)

This seaming scheme was considered to be the most desirable

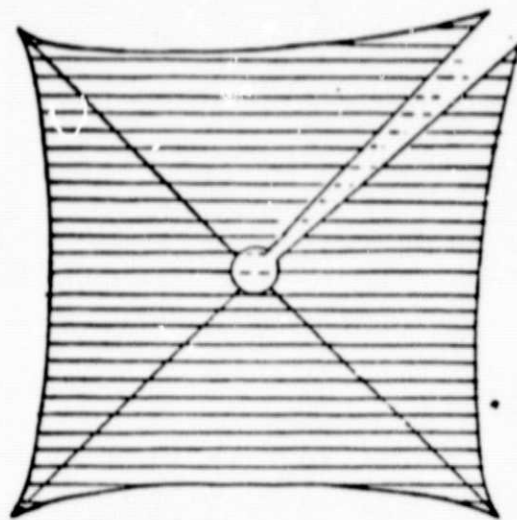


FIGURE 6-1

SEAMS PARALLEL TO ONE SIDE

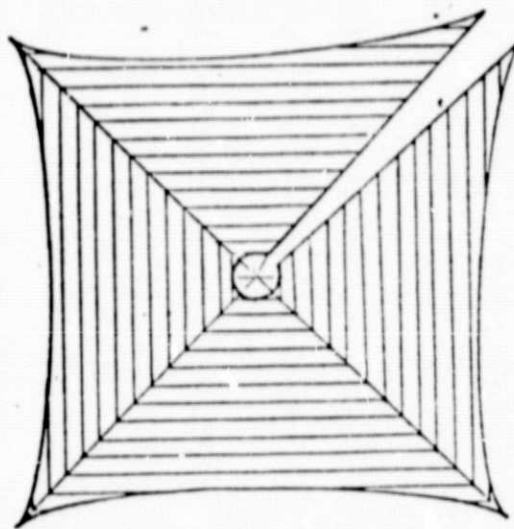


FIGURE 6-2

SEAMS PARALLEL TO SIDES

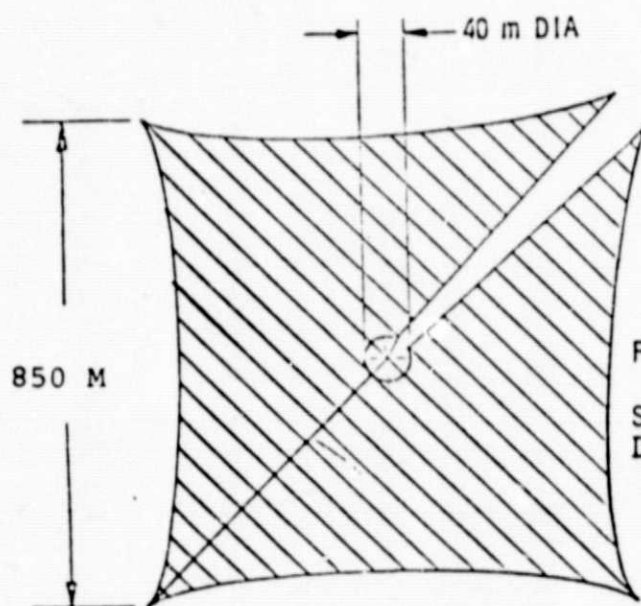


FIGURE 6-3

SEAMS PARALLEL TO ONE
DIAGONAL

from a standpoint of continuous reliable fabrication. Patterning would be controlled by the stipulation that seams approach and leave two of the diagonals in a continuous and perpendicular fashion. If this guideline is guaranteed, there would be no requirement for pleating or cutting the basic film at these two diagonals. In this manner the sail would be continuously fabricated in two halves and then joined together along the other diagonals.

6.2 Goring Scheme

It is desired to pattern the sail in a manner which is consistent in form and configuration with the intended manufacturing process. It is believed that a goring technique which affords nearly full available width material strips with minimum variations is desirable. Toward this end, a goring scheme was considered which would establish straight-line progressions across the sail surface. These lines were constrained to leave the diagonal reinforcements such that they were perpendicular in the plane of the sail, not in the planform.

It was proposed to have the computer develop a family of such lines and then calculate separation distances between adjacent lines. The lines would then be moved such that their maximum separation from adjacent lines was one material panel width. Later it was considered to modify this requirement and consider separation distances of various multiples of panel width. In this concept, a multi-panel subassembly would be pre-fabricated prior to integration with the accumulating sail.

The proposed goring scheme is described below:

Figure 6-4 represents a gore or panel centerline perpendicular to a segment of a diagonal. The intent of this scheme is to follow that centerline as it transverses the sail.

A step iteration is described below in which we use simple geometry to follow the progression of this line and, in fact, a family of such lines in both the plane of the sail and the projection.

See Figure 1.

It is assumed that an equation for the general sail surface exists and can calculate Z for any X, Y in the projection.

Convention: X_{AB}

A. denotes point number (1-4)

B. denotes projection plane (1) or sail surface directly above (2).

	Unit Lengths L_1, L_2		
Known Values:	X_{11}	Y_{11}	
	X_{21}	Y_{21}	
	X_{12}	Y_{12}	Z_{12}
	X_{22}	Y_{22}	Z_{22}
	Z_{32}		

Right angles in sail plane

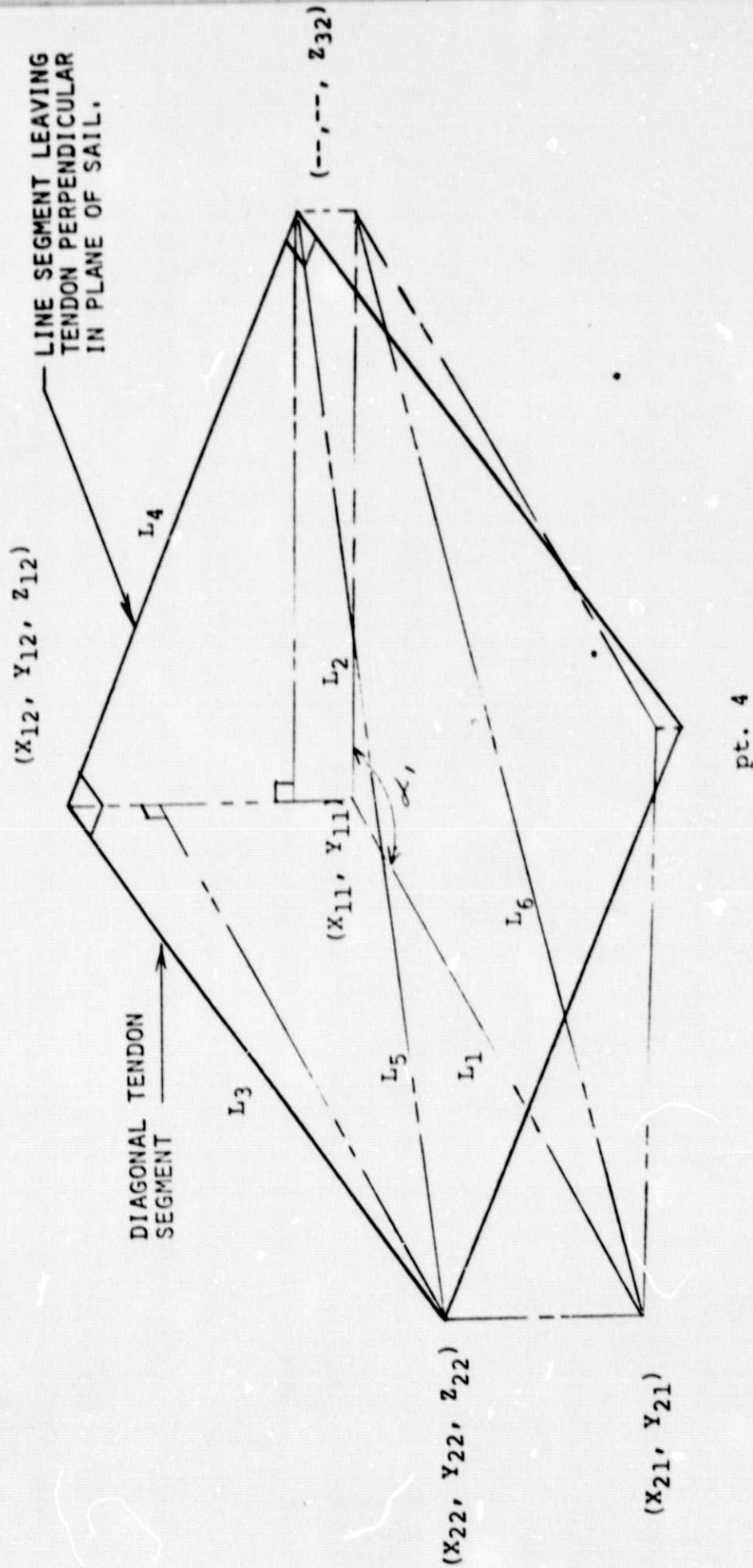


FIGURE 6-4
GORE SCHEME SCHEMATIC

Procedure: Find L_3, L_4
Find L_5
Find L_6
Find $\alpha,$
Find (X_{31}, Y_{31}) using calculated
Find (X_{32}, Y_{32}) same as above

Store location of point 3 in projection and on surface.

Store L_4 .

We have now identified the end point of a directed line segment of length L_4 which leaves the diagonal tendons perpendicular. We have identified its location in both the projection and the sail surface.

To begin next iteration to find locations of next line segment end point we must first:

Find point 4 (X_{41}, X_{42}) using calculated

Find Z_{42} using surface equation

Make substitution:

Point 4 becomes new point 2

Point 3 becomes new point 1

Find new point 3 from unit length L_2 and surface equation.

Assumption: This scheme assumes the projection plane angle to be 90° only to find 2 valves of point 3 in each iteration. Error is very small.

This scheme develops projection trace of panel centerlines which are perpendicular to diagonal tendons. Several such lines are developed, say every 10-20 meters along diagonal.

To develop panels between the family of lines developed above, we can have the computer move equal distances down adjacent lines and calculate distances between corresponding points. This distance can be divided by even number of panels based on largest separation distance. The results would be several main centerlines with flat (or curved) panels between them.

It is envisioned that the panel definitions could be maintained by a computer and used to guide a cutting device during manufacture. The area between main centerlines could be filled with all moderately variable gores or could be filled with several straight panels and only a few drastically shaped gores.

It was intended to test this scheme on the computer. The plane geometry equation for calculating the various lengths and angles from the known values for each iteration were generated; however, a computer program was not written to perform the computation prior to program redirection.

6.3.1 Feeding

The feeding of 1 meter wide rolls, either singly or in multiples, will be similar to the methods proposed for fabricating the spinning sail. The feeding of the accumulated layers, however, present problems when the folded sail is rolled up in one piece. When nearing the completion of fabrication, most of the material, including seam tapes, ripstops, reinforcements, etc., will have to be unrolled to be fed to the sealing head(s). The repetition of rolling-unrolling of the accumulated layers could deteriorate the sail film coatings and/or otherwise damage the sail.

The feed and take-up rolls will be driven and their rotational speed synchronized to the other operations so that only minimum loads are placed on the sail film. The feed and take-up rolls will be designed with a large diameter to minimize flexing of the sail components. If a single direction fabrication concept is used, the take-up roll, after 1 single pass operation is completed, would be carried around and used as the feed roll for the next operation. It is obvious that when the take-up roll is now placed in the feed roll position, the opposite side of the sail film will be on top. The 1 meter wide feed rolls of Kapton and the sealing head(s) must now be inverted or be duplicated above and below to be used alternately. The longest length for a run would be diagonally approximately 1202 meters (3944 feet). Although it is anticipated that length of material on the feed rolls will exceed this length, provisions must be

made for splicing in new rolls and/or replacing defective sections. The splicing would be done with tape over sail film butt joints.

If a reversing feed concept is used (Figure 6-5), the sail film would not be completely unrolled from take-up or feed rolls but would be wound by means of leaders or non-functional extensions of the accumulated layers that would be removed at the completion of fabrication.

Here again, in one direction the sun side of the film would be up, and in the other, it would be down.

6.3.2 Sealing

The sealing requirements of the square sail are the same as those for the spinning sail in the film to film sealing. Refer to Section 4.2 and Figure 4-5. With regard to sealing the sail film to diagonals and scalloped edges the following is proposed:

- For the diagonals, a prepreg tape similar to that used for the catenary edges of the spinning sail would be proposed. The sail film would be heat sealed to the tape similar to the spinning sail concept.
- For the scalloped edges, a prepreg tape similar to that used for the diagonals would be used and sealed in a like manner.

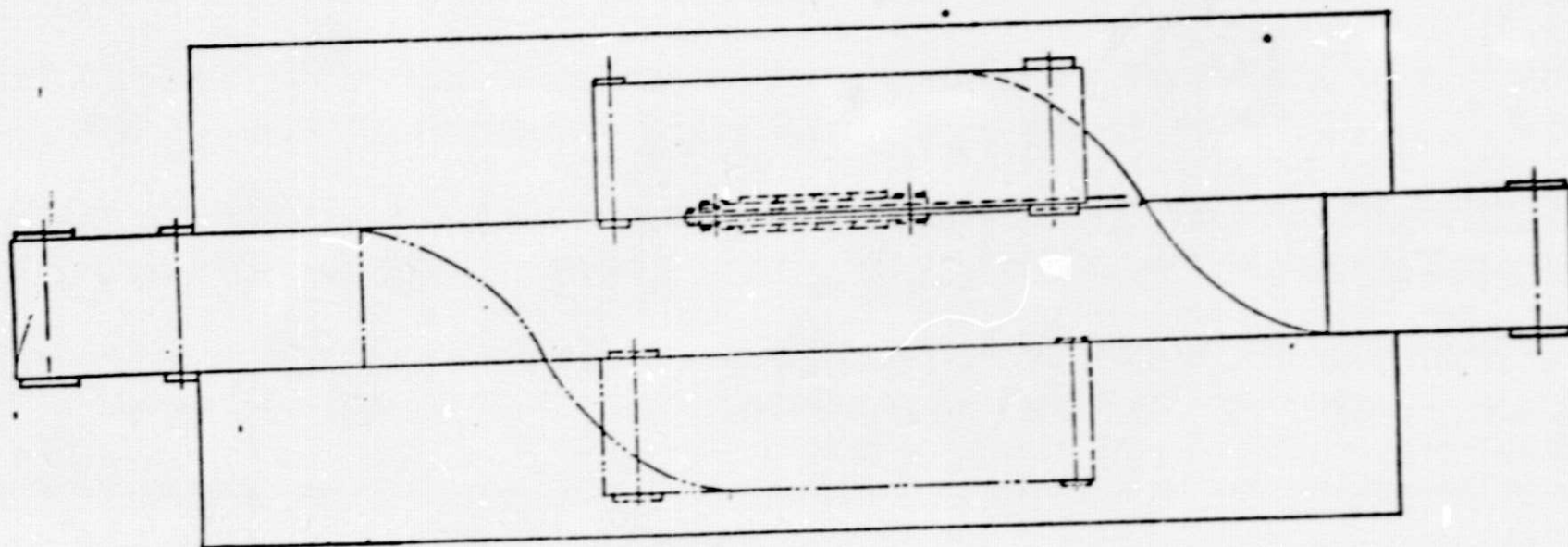
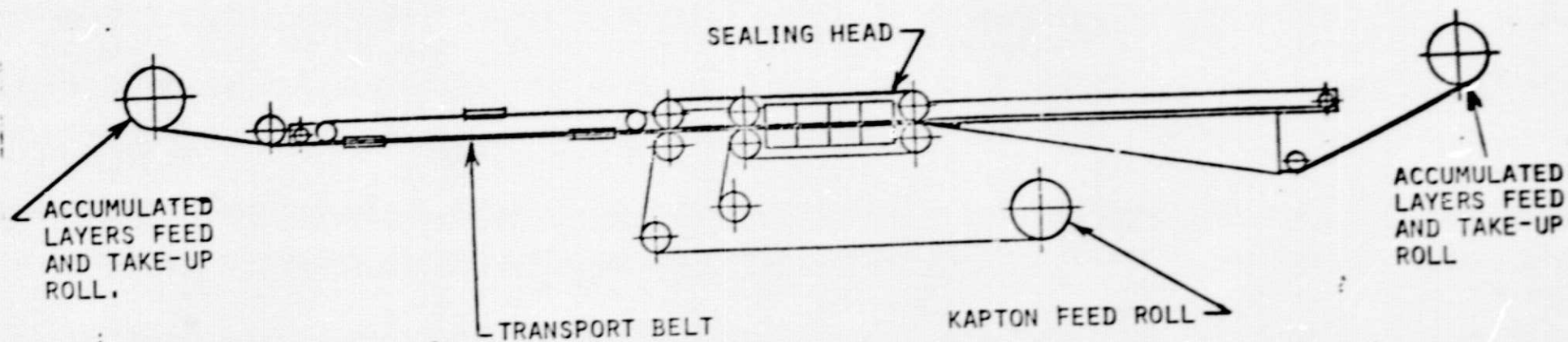


FIGURE 6-5 REVERSING FEED CONCEPT

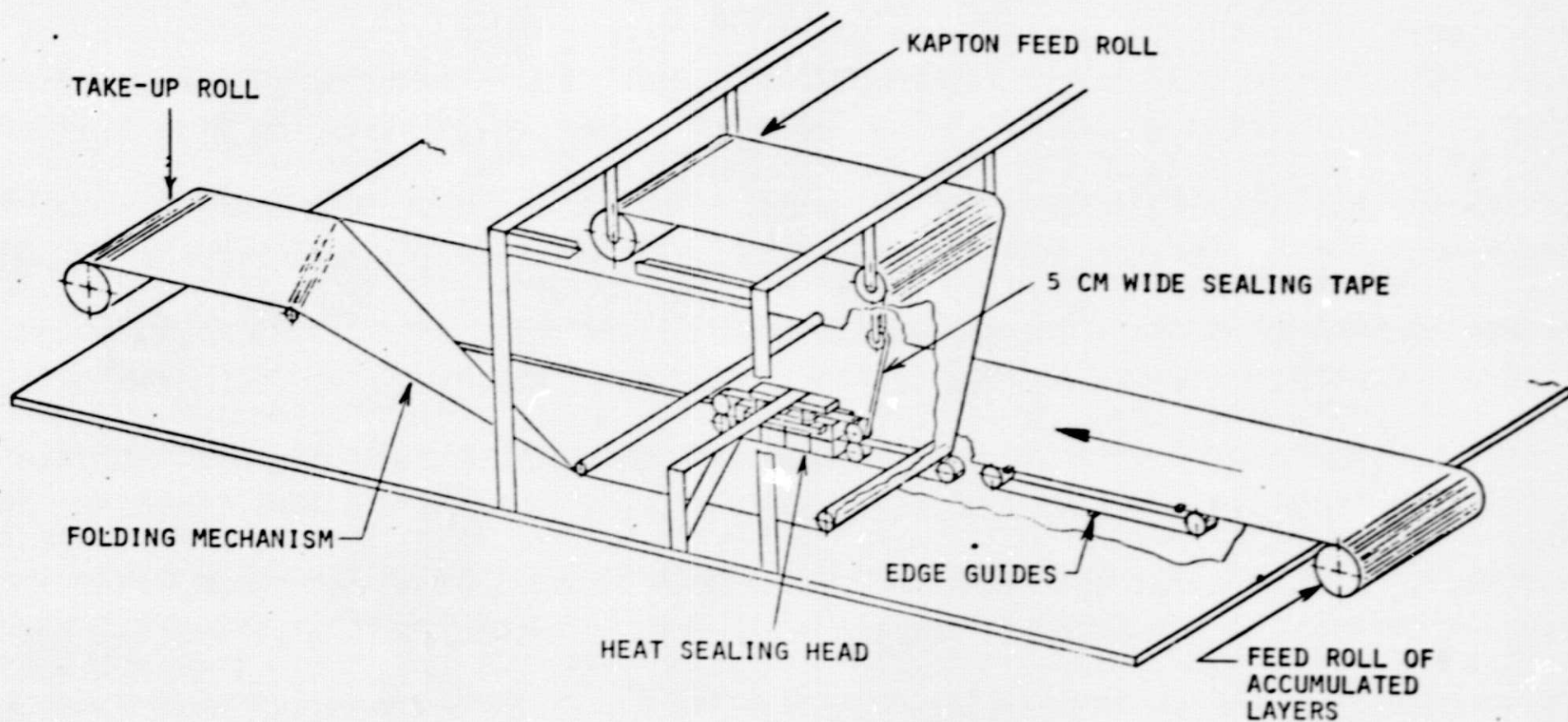


FIGURE 6-6
FILM TO FILM BUTT SEALING WITH OVERTAPE

6.3.3 Folding

The most difficult part of the fabrication plan is the folding because of the following:

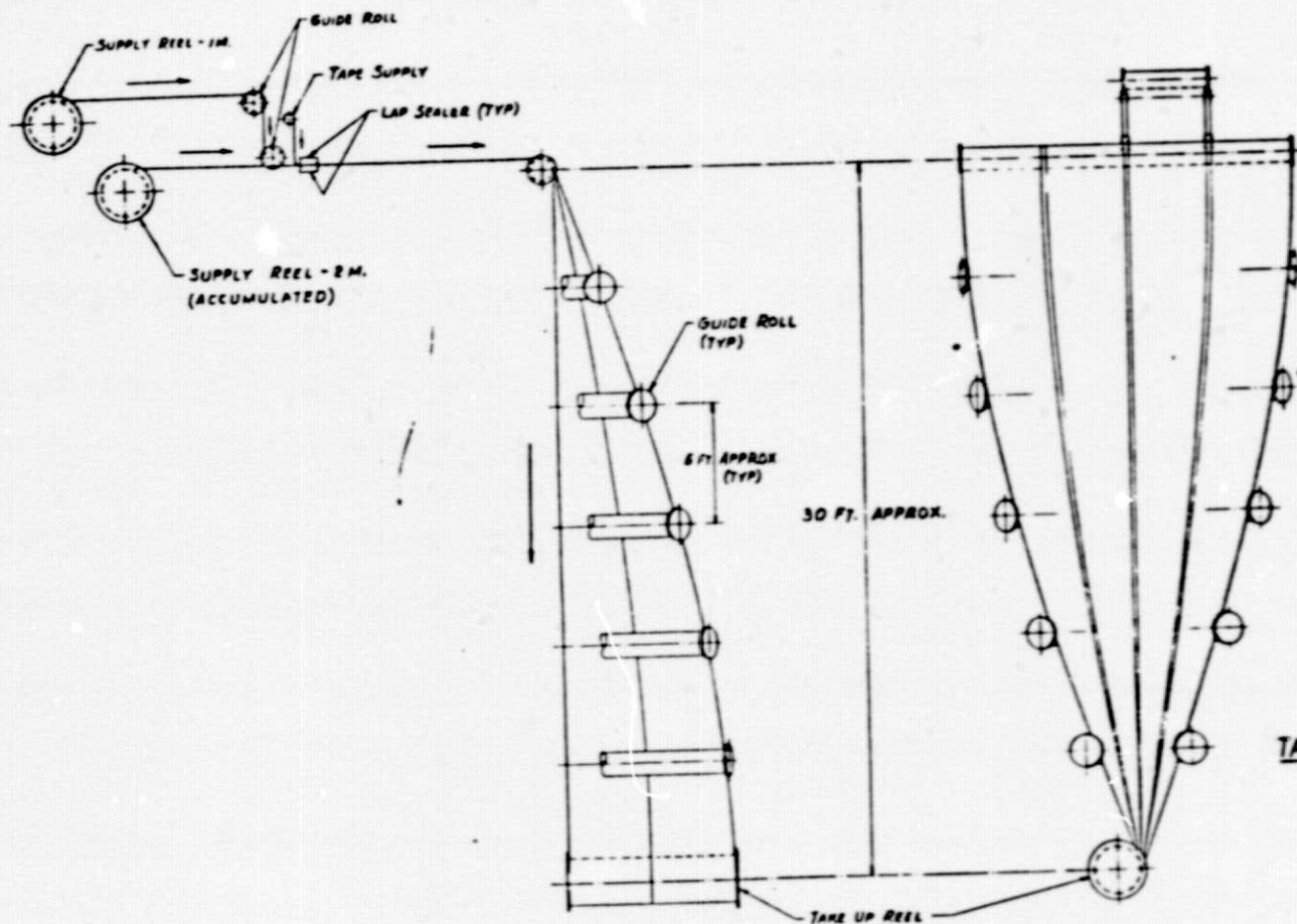
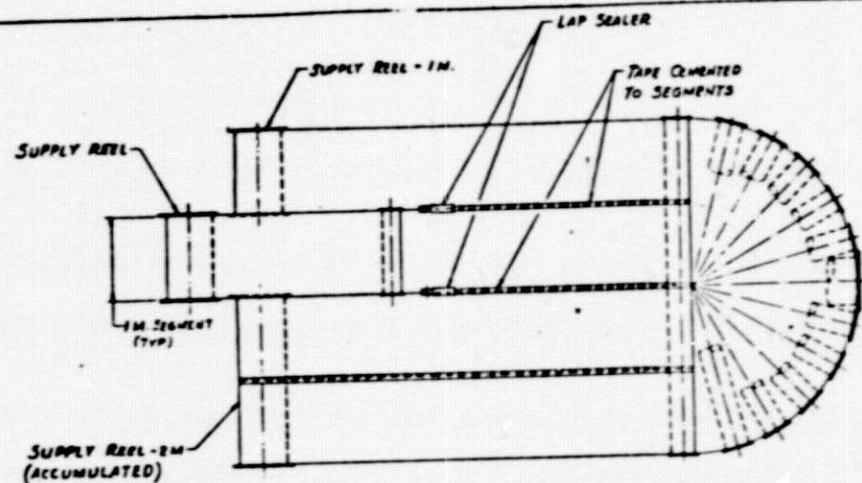
- Thinness and uncontrollability of the 0.1 mil Kapton.
- Great expanse of material, 850 M square.
- Necessity of rolling and folding sail in one piece.

Various methods of folding and transporting the film have been studied. The sketches and notations described as follows will explain the studied methods.

6.3.3.1 Vertical Drop Fold SK77-0027 (Figure 6-7) - The accumulating layers are fed out horizontally to the tape sealing head; the width of these layers is 2 meters. Two feed rolls of Kapton, each 1 meter wide, are fed horizontally to the sealing heads so that a single film is joined to the top film of the built-up layers and simultaneously another 1 meter wide film is joined to this single film. The total material width is then four meters.

The joined films advance to the drop-off roller and fall vertically while each being folded or twisted 90° . The main advantage of this arrangement is that indexing problems between accumulated sail and the single layer added film are eliminated since each of the folds travels the same distance.

The great disadvantage of this arrangement is that every other pass, when the accumulated layers on the take-up roll are moved



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TAPED BUTT SEALER & FOLDING CONCEPT

VERTICAL DROP FOLD

SK 77-0027

S.M. 8-4-77
FIGURE 6-7

to the feed position, the tape sealing must be done from the underside due to the fact that the aluminized side is facing downward every other run. Another disadvantage is that the vertical drop (30 feet) could be much greater and then would necessitate a fabrication facility not only of great length but of great height as well. Control of inter-ply shear caused by accumulated material weight during the vertical drop is a serious problem with this scheme, also.

6.3.3.2 Double Vertical Fold SK77-0028 (Figure 6-8) - In this concept, the 4 meter wide films, which have been sealed together are both lifted and rotated from a horizontal to a vertical position where the 2 meter wide accumulated layers are rolled up on a vertical take-up reel. A disadvantage of this concept is the tendency of the film to slide down or drop as it approaches the vertical position. An advantage is the accessibility to the work area.

6.3.3.3 Double Horizontal Fold SK77-0029 (Figure 6-9) - In this concept, one half of the 4 meter wide film is folded through 180° to lay on top of the accumulated layers by means of guide rollers.

The greatest disadvantage of this concept is that one edge (the one rotated 180°) has to travel a greater distance than the opposite one causing alignment problems necessitating a complicated corrective mechanism to regain line to line indexing of adjacent panels.

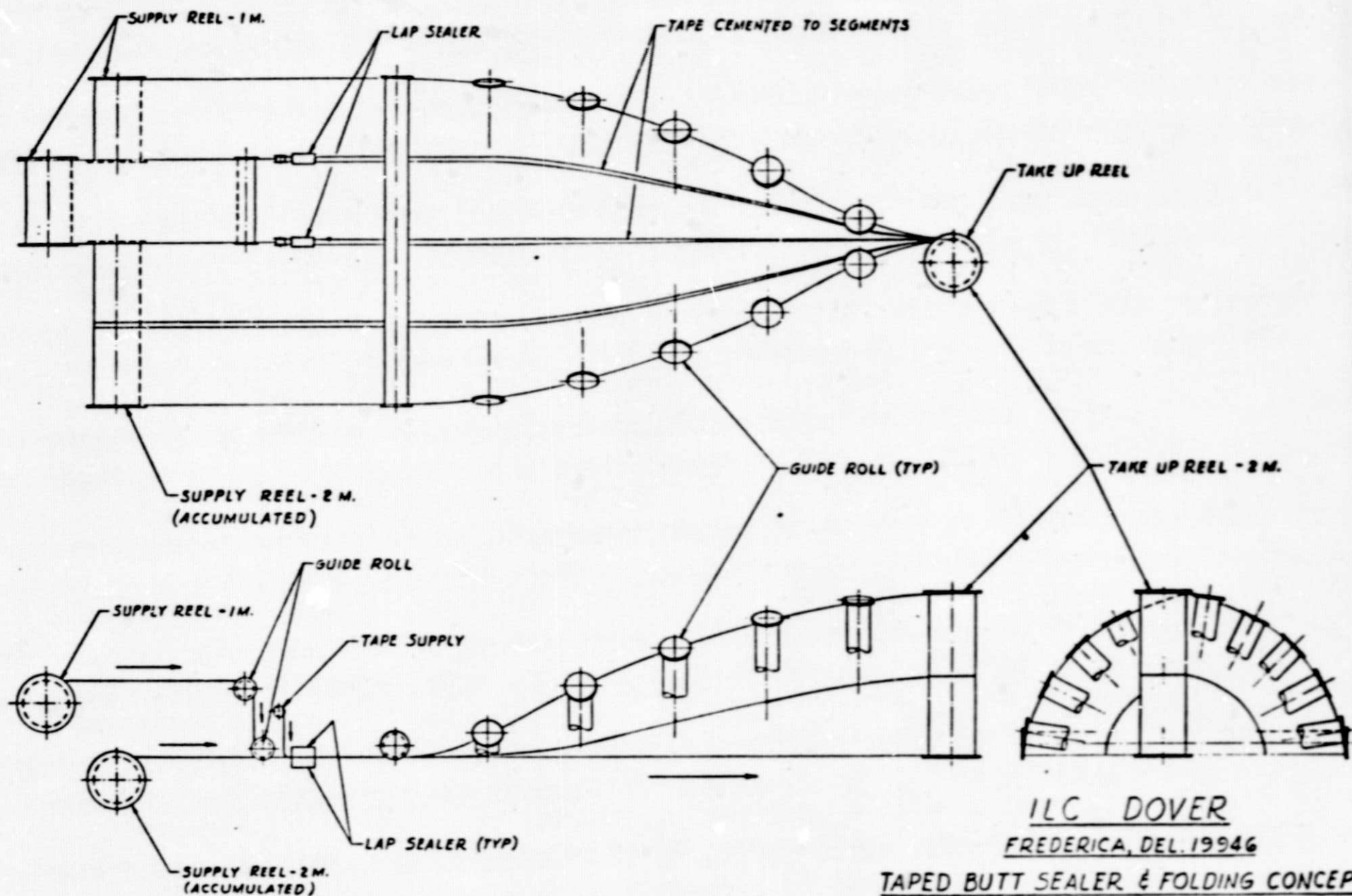


FIGURE 6-8

SK 77-0028

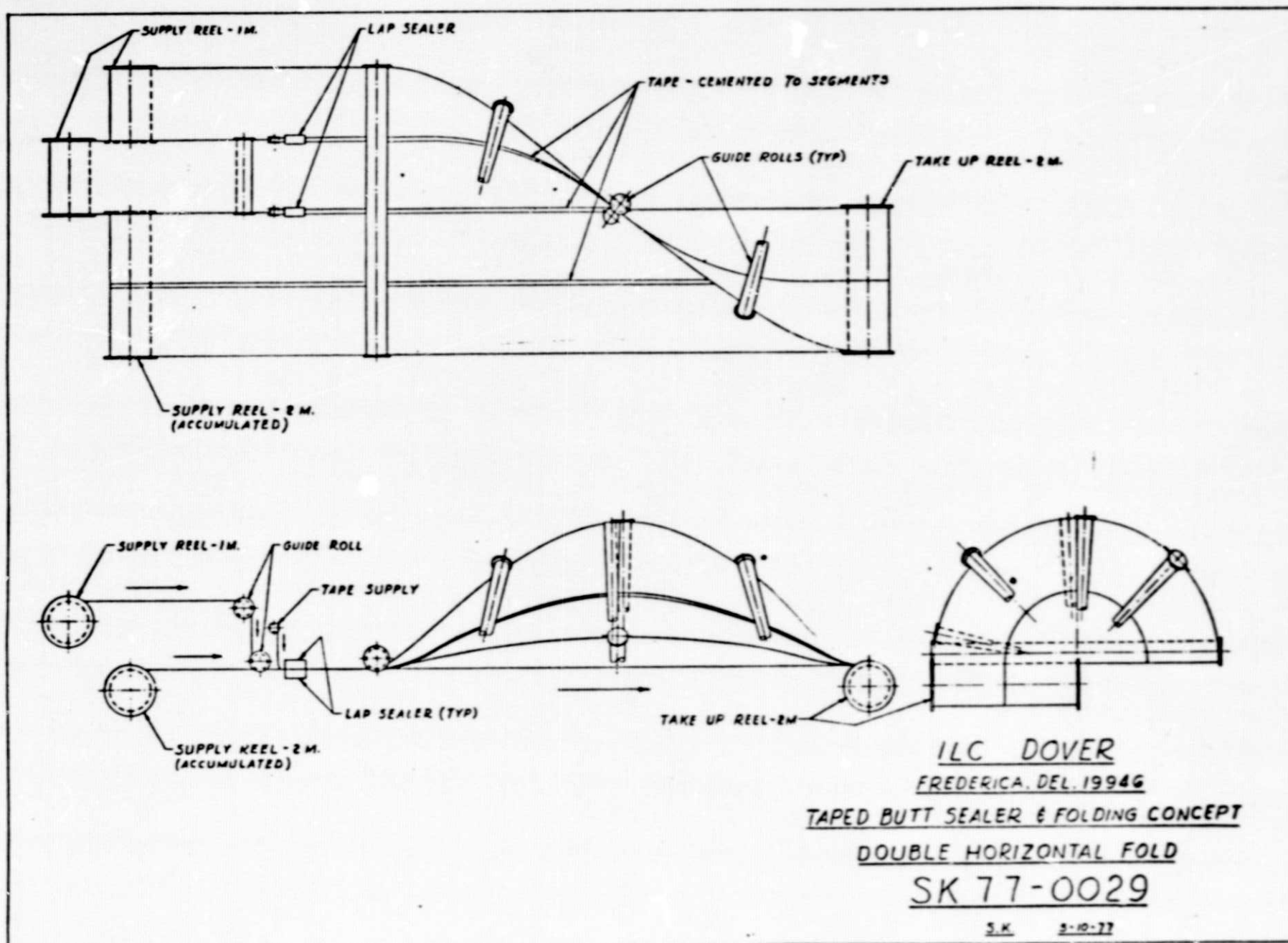


FIGURE 6-9

6.3.3.4 Four Panel Z-fold Over Air Surface SK77-0033 (Figure 6-10) - This concept requires that a 6 meter wide film sheet be fed to the Z-fold mechanism. The 6 meter width is made up of a 2-meter width of accumulated layers being fed from storage rolls and a 4-meter width composed of 1-meter wide films being supplied from new material feed rolls. The Z-fold mechanism simultaneously folds the 4-meter wide single layer addition into a 2-meter wide double layer and also positions the whole assembly on the accumulated layers. The film is guided from the 6-meter flat shape to the 2-meter wide shape (after Z-folding) by inside and outside shape guides as per Figure X. The shape guides are pressurized and have a multitude of directed holes so that the film is directed and rides along an "air-bearing" surface. These air holes or jets are directed so that the Kapton film is kept smoothed out and pushed in the direction of the take-up reel. The advantages of this concept are:

- Less abrasion and related handling damage to the film because film is transported on an air bearing.
- Less fabrication time because 4-meter wide films are added simultaneously.
- Same edge and same side of material presented to sealing heads each pass.

Some of the disadvantages are:

- The great areas of sheet metal required for the inside and outside folded shapes.

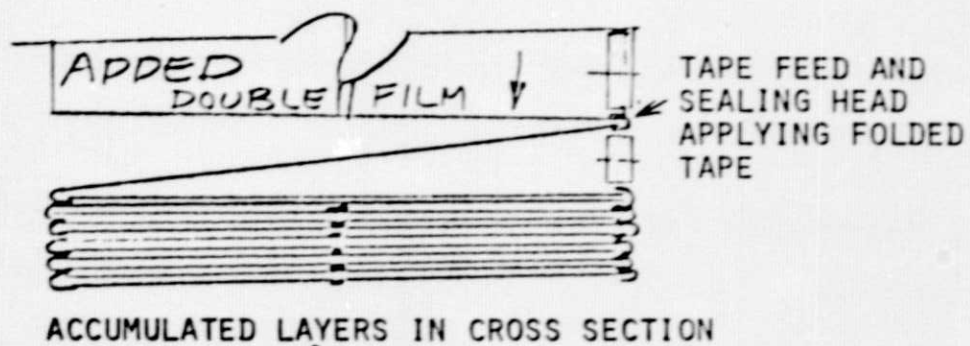
- The great number of holes and the proper angles to direct the air jets.
- Alignment problems as the folded edge has to travel a greater distance than the opposite edge.

6.3.3.5 Folded Tape Concept (Figure 6-11) - This concept was devised to avoid the problems associated with folding the film over onto the accumulated layers as in the previous concepts. Here a film from a feed roll 2-meters wide (or two reels of one meter wide with sealing head with tape) is fed on top of the accumulated layers. Before the film lays flat on the accumulated layers, a folded edge tape is sealed to the film edges; i.e., free edge of accumulated layers and one edge of newly fed film.

The great advantage of this concept is that the complicated folding mechanisms and attendant problems are avoided. A secondary advantage is the simplified addition of film from feed rolls with easier alignment.

A disadvantage is that the folded tape is located on alternate sides of the film when the sail is deployed. At the seams where the tape is on the shade side, it would be most difficult to maintain a 0.3 mil or less gap as required for temperature control. Applying a pre-folded tape inside of the two edges to be sealed would be quite difficult to accomplish and control.

Another disadvantage is that the film adjacent to the edge seal tapes could stick together and to the sealing tape, thus preventing the sail from opening properly when deployed. High film temperatures would be caused by this occurrence.



* ADDED DOUBLE WIDE SHEET FED FROM ABOVE

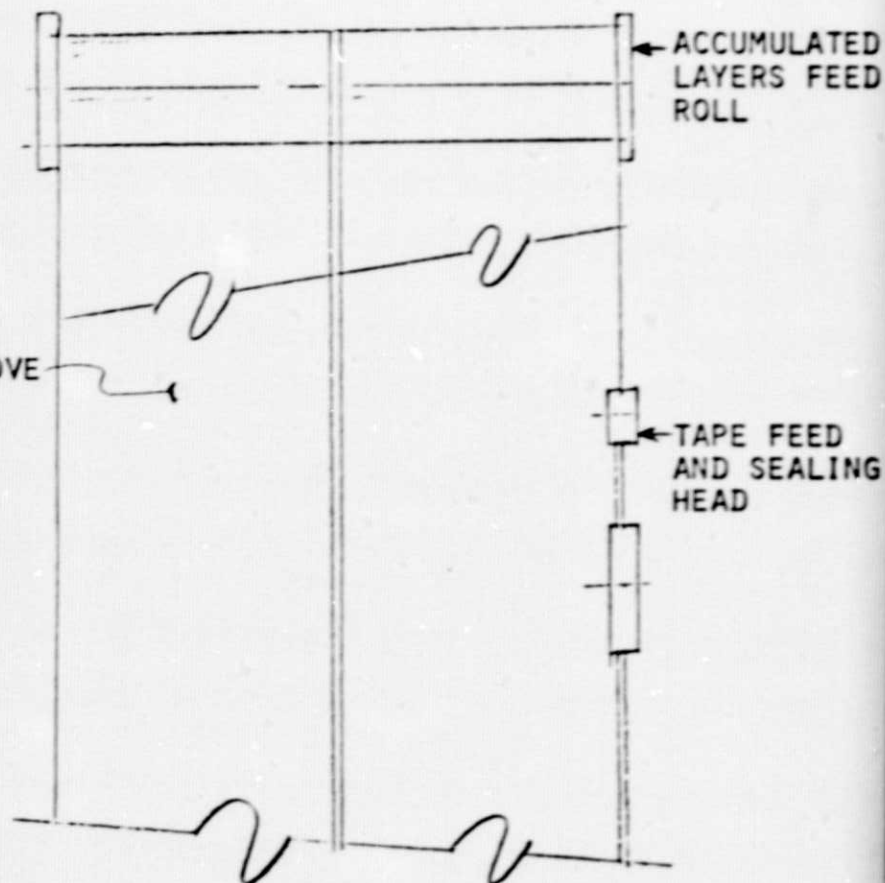
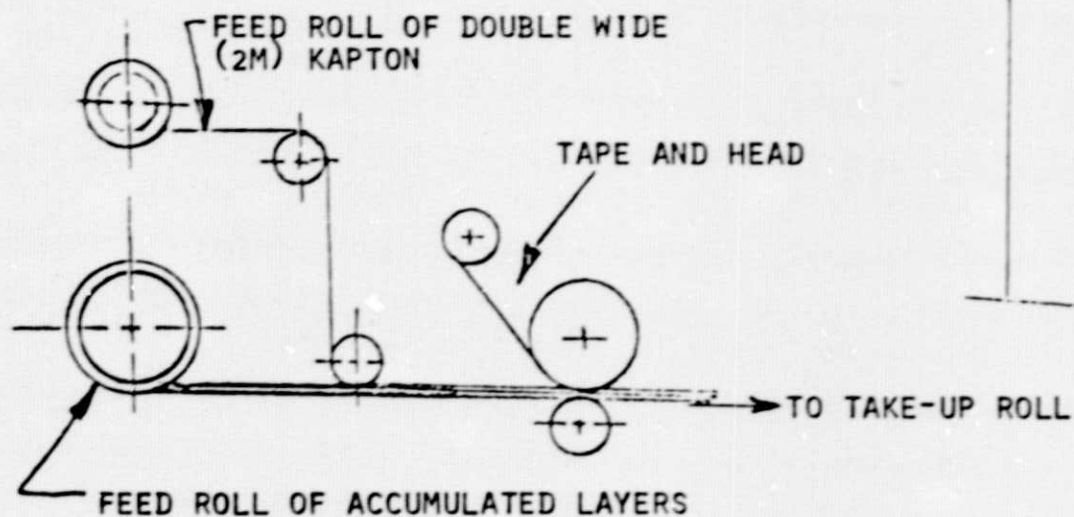


FIGURE 6-11

FOLDED TAPE CONCEPT

6.3.4 Take-up

As the new 1 meter wide films of Kapton are added, the accumulated layers are rolled and unrolled until the sail is complete and wound around a take-up reel. The rolled sail then must be folded into a Zig-Zag, half circle, accordian fold for stowage in the Space Shuttle Cargo Hold per Figure 6-12. This stowage shape is necessary for the planned deployment in space as depicted in Figures 6-13 and 6-14. This folding can be done around a form assisted by hand with a simple oscillating arm roll suspension device.

6.4 Special Fabrication Problems

6.4.1 Diagonals

The diagonals will follow the shape per computer direction. It is planned to make the diagonals of similar construction to the edge member catenaries described in 3.4.2.2, Unidirectional Graphite Filament prepreg tape. The diagonal lengths, approximately 580 meters each, will have to be added in one, two, or four meter wide segments as the film edge sealing takes place.

The film will be heat sealed to the diagonal. The film sealing would be stopped midway along the length of film sheet being added to permit a crosswise sealing in a segment of the diagonal which would sufficiently overlap the previously added tape to meet strength requirements. The diagonal segment would be added perpendicular to the table per the shaping plan. The diagonal will be installed to the shade side of the sail.

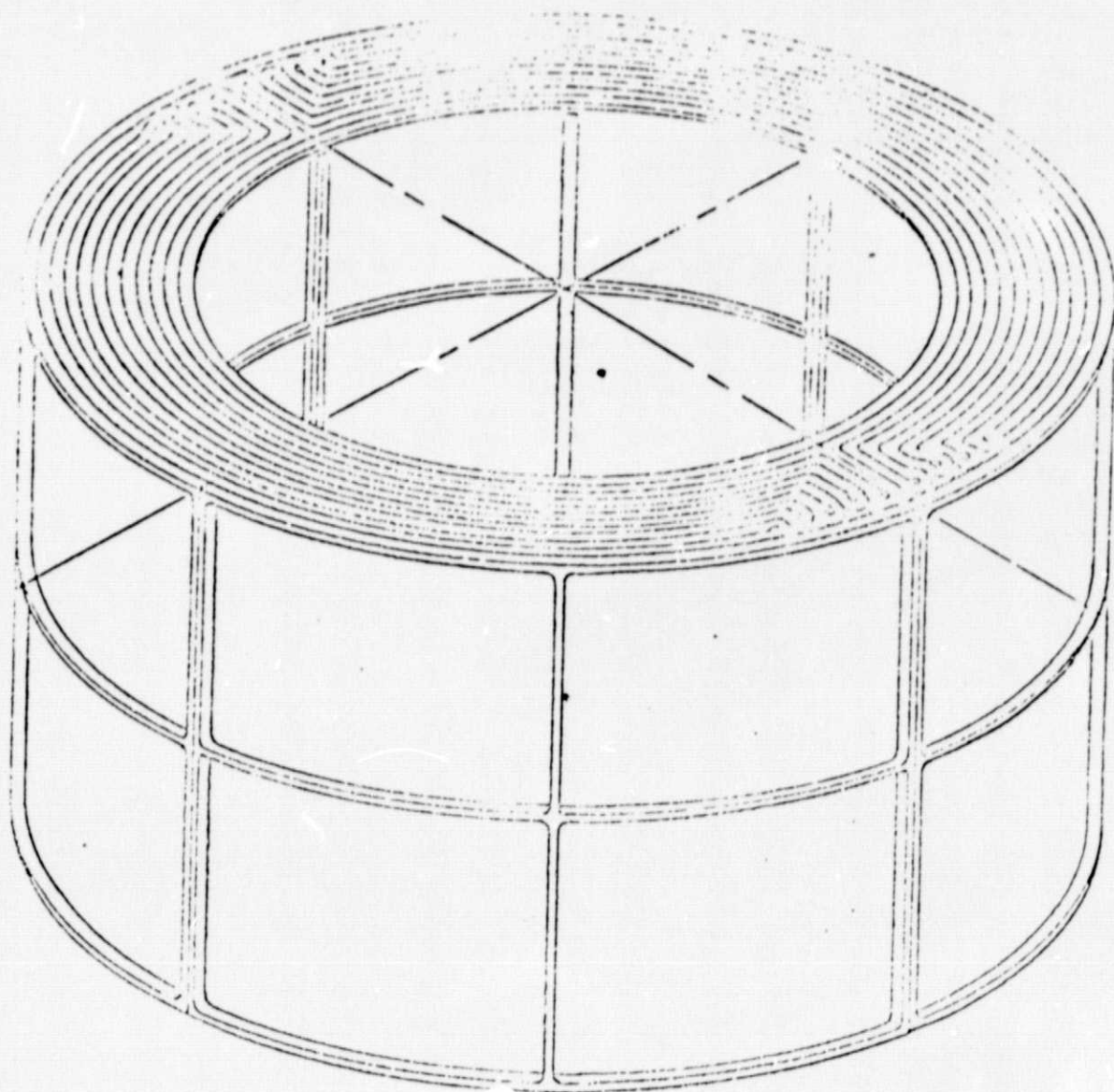


FIGURE 6-12
COMPLETED FOLDED SAIL

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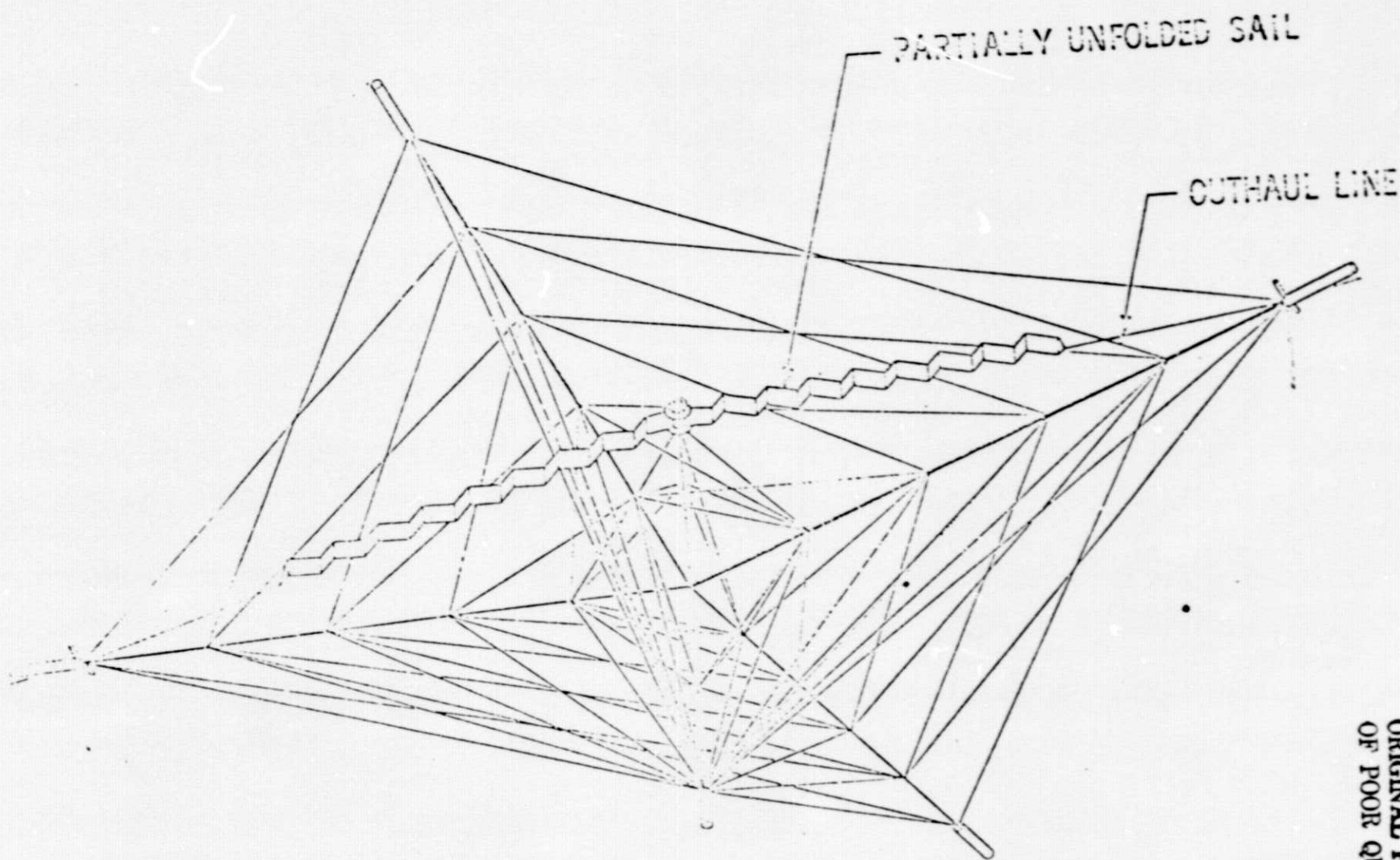


FIGURE 6-13
UNFOLDING SAIL, FIRST AXIS

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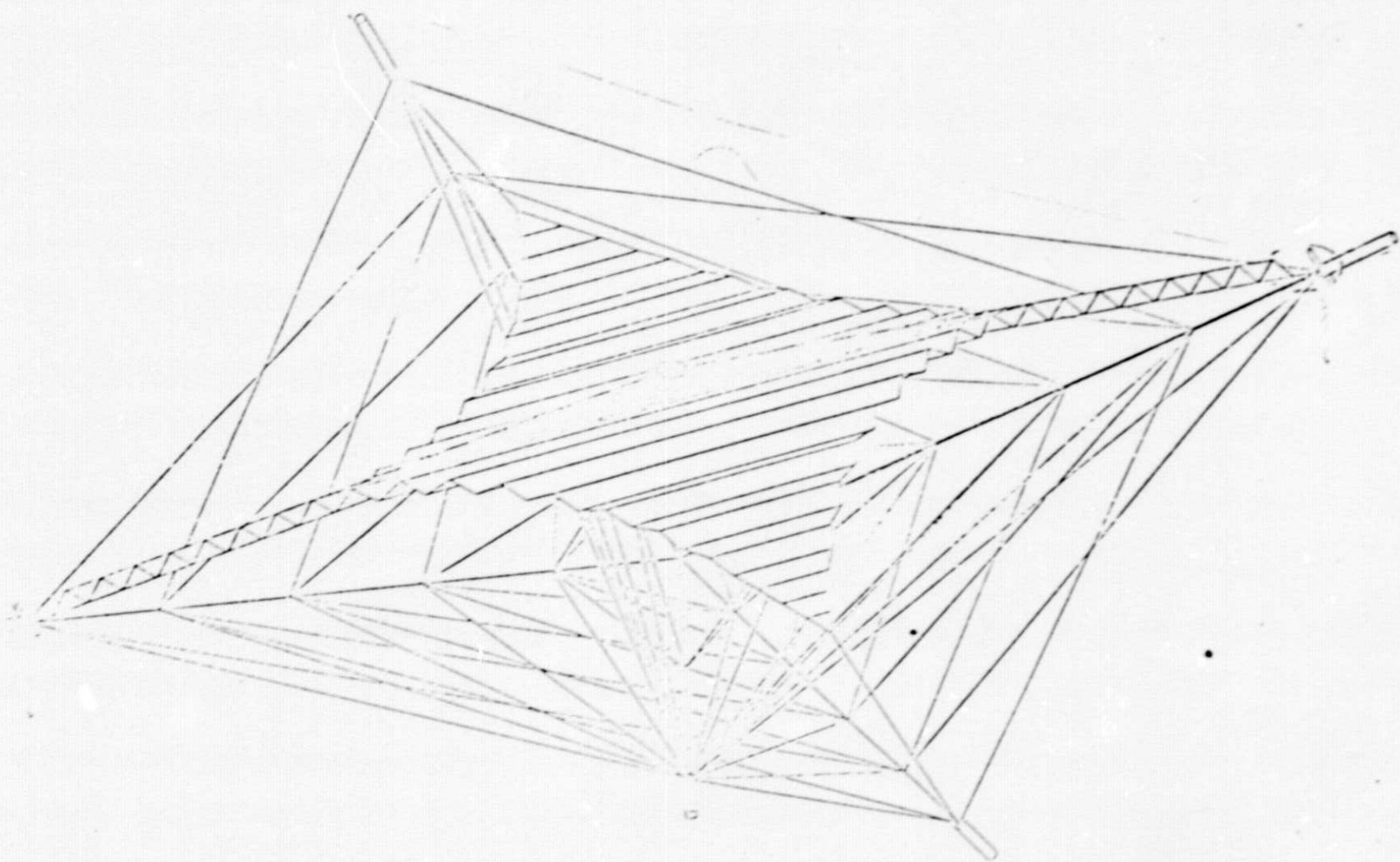


FIGURE 6-14
UNFOLDING SAIL, SECOND AXIS

6.4.2 Edges

The scallop edge reinforcements must also be sealed to the film in segments as the sail is being fabricated. Their exact angle and location (cut-off of film sheet) will be computer programmed. These segments will overlap the previous scallop segment. Their construction will be similar to the diagonals with thickness sized to scallop stress level requirements.

6.4.3 Hole

The center hole is 40 meters (131 feet) in diameter. This hole is necessary for clearance of the payload instrumentation and for temperature control criteria. This hole will not be a circle but will probably have an epicycloidal shape due to the stress distribution. The diagonals will terminate at the four points of this hole and be suspended from the payload structure by inhaul lines. These lines are adjustable for trim to position and tension the sail to obtain best performance. The edge reinforcement for this hole will be similar to the tape used for the diagonals and the scalloped outer edges but of thickness to suit the hole stress levels. As the new 1 meter wide layers of Kapton are being added to the accumulated layers, the fabrication operation will be stopped to seal in the piece of hole edge tape and cut the film to the hole shape. When fabricating across the hole area, the process will have to be interrupted when the hole edge is reached to add the applicable edge reinforcement and cut off the film. Then the accumulated layers will be taken up until the sealing heads, etc., reach the place where

the hole ends, there to add edgemember, etc. It will be difficult to pick up the edge again but a tenter frame and clamps could be used to attain correct indexing.

6.5 Testing and Modeling

Studies, mock-ups and models were made of various fabrication and handling concepts/components to determine the problems involved and solutions thereof. A compendium of these efforts follows:

6.5.1 Rolling Sealer with Seam Tape

This concept was mocked-up and rough modeled to access the difficulty of guiding two film panels into a tape feeding head. The obvious problem was the transport of the two film edges to the sealer and the sealed film away from the heat. A tenter frame with hooks or clamps to hold and index the film edges was proposed. This frame would have to move in synchronization with the rolling sealer head. The Kapton material, 0.1 mil thick is so flimsy that it will not lay down and must be held in place and transported by tenter frame conveyors, air pressure, etc.

6.5.2 Pressurized Rods

One half inch diameter aluminum tubes were used in pairs to investigate the capability of an air jet surface to move the film along and smooth out wrinkles. During this exercise, it became obvious that the rods would have to be so close to each other to maintain the film in a non-wrinkled state that a continuous air cushion surface would be much more efficient.

6.5.3 Air Cushion Chute

A cardboard mock-up of this concept was built and used as a folding guide without air holes in its surface. The Kapton film was pulled along manually from a supply roll. The chute would be internally pressurized in practice; directed air-jet holes would create an air cushion or boundary layer moving the film and keeping it wrinkle free. This concept was considered the most feasible and SK77-0033 was developed. Instead of two pressurized rods to move the film, a pressurized chute to create a directed air bearing surface is on one side of the film and pressurized rods on the other. This arrangement would permit visual inspection of the sail film during fabrication through the rod assembly.